A CRITICAL REVIEW OF LITERATURE ON COOLING OF INJECTION MOULDS

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ABSTRACT

The paper presents a critical review of the techniques that are used to cool plastic injection moulds. It examines research on cooling of injection moulds by conventional cooling, the benefits and the limitations of the method. It compares the deployment mechanisms that have been proposed by various researchers. It also examines how the various mechanisms affect the plastic cooling rate and the overall heat transfer performance of the mould and how the various deployments affect the stress distribution of the mould and mould durability.

The paper also presents the possibilities that have been presented by rapid prototyping. It discusses the development of conformal cooling as an alternative to conventional cooling. It presents the state of the art on the method. The paper presents the deficiencies in the current theories on conformal cooling and suggests areas that require further work in order to fully exploit the technique.

Key words: Cool plastic injection moulds, rapid prototyping

1 INTRODUCTION

The plastics industry has grown tremendously in the past few decades. Components ranging from cell phones parts to toys are made from plastics. There are two main techniques that are used to manufacture plastics; blow moulding and injection moulding. Injection moulding is usually the preferred method of manufacture as complex shapes and geometries can be made. An injection moulding process can be divided into four crucial sub divisions; filling, packing, cooling and ejection (Tang et al, 2006). Cooling is the most crucial of the four stages as it affects both production cycle time and quality of the moulded plastic.

However, problems of cooling have always plagued the production of plastics through injection moulding. Two major techniques have developed over the past ten years to address the cooling problem and provide a constant mould surface temperature and promote the transfer of heat from the cooling plastics. Constant mould surface temperature is crucial in prevention of the development of residual temperature induced stresses in the moulded plastics and in the retention of dimensional proportions. Prior to the development of rapid prototyping, the coolant was passed through holes that were drilled through the mould. The structure of the cooling channels was limited by the mould production techniques that were available at the time and did not address the cooling problem satisfactorily. Conventional manufacturing techniques can produce complex external geometries but can develop only limited internal geometries. Despite this limitation, cooling using drilled holes is the most widely used technique for transport of coolant used in cooling injection moulds.

The advent of rapid prototyping, an additive manufacturing method, has opened up the possibility of addressing the cooling problem without being limited by production techniques. Rapid prototyping enables manufacture of complex internal and external geometries. Rapid tooling is a subset of Rapid Prototyping and Manufacturing (RP & M) that has grown in importance over the last few years. There are several technologies such as Stereolithography (SL), Laser Sintering[1] (LS), 3 Dimensional Printing et *cetera* under the umbrella of RP & M but in all, the prototype is made layer by layer from 3 dimensional CAD models. LS, which creates 3 dimensional objects from powder materials, has emerged as the most versatile RP & M process with regard to the materials that can be used. LS has enabled the development of hard tools for full production runs.

The flexibility provided by LS, among other technologies, has facilitated the development of conformal cooling of injection moulds. In conformal cooling, the cooling channels follow the contours of the mould surface. The technique offers more promise in mitigating the cooling problem but more work is required to fully develop the technique. The heat transfer requirements demand that the cooling channels be as close as possible to the mould surface. On the other hand, structural integrity requires considerable spacing between the mould surface and the cooling channels.

2. STATE OF THE ART

Researchers have attempted various techniques to facilitate high heat transfer rates and to achieve uniform mould surface temperature. Conventional cooling of moulds has been extensively studied in literature and a common solution has been adopted. Due to tooling limitations, the preferred cooling technique has been to drill holes through the mould and pass coolant through them. Researchers such as Lee et al (2005), Li (2000) have provided guidelines on the size and deployment of the cooling holes. Others like Sun et al (2002, 2004) have investigated other configurations of cooling channels such as milled grooves. However, it has been recognised by most of these researchers that the convectional techniques of cooling that have failed to achieve constant temperatures at the mould surfaces except for simple geometries. Lee et al (2005) propose investigation into the possibility of using parallel channels to cool moulds. Although the technique performs better, it still deficient as it is not possible to achieve constant heat paths that are necessary for even mould surface temperature.

Over the last decade, Rapid Prototyping and Manufacturing (RP & M) has extended its application to the production of tools both for short production runs (soft tooling) and for full production runs (hard tooling). In RP & M, the components are formed layer by layer. This mode of formation enables

[1] - Two international companies (3DSystems (SLS) and EOS (LS) held patents selective laser sintering patents. After a court-case which lasted close to three years, the companies settled and agreed to use different trade names, as referred to (SLS & LS). Currently, only LS-technologies are available in SA.

incorporation of intricate internal structures that can be used as cooling channels. It was reasoned by previous researchers that if the channels followed the form of the mould surface, then high cooling rates of the moulded plastic could be achieved. Dimla et al (2005), Ferreira and Mateus (2003), Dalgarno and Stewart (2001a, 2001b) and Sachs et al (2000) have all investigated and recommended the use of conformal channels. All of these researchers provide qualitative guidelines for the design of the conformal channels to maximise heat transfer while retaining structural integrity. They all agree that the channels should be circular and as close as possible to the mould surface. However, what is required is quantitative definition of channel position and configuration.

Sachs et al (2000) provide a comparison of conformal channels with drilled cooling holes. They found that conformal channels perform better than drilled holes. Their work is compromised, however, by their use of 303 stainless steel for drilled moulds and 316 L spherical stainless steel powder with acrylic binder for the 3 D printed moulds. The printed moulds had a porosity of 32 %. These two test pieces have such contrasting thermal properties that their comparison does not validate the theory. Sachs et al (2000) suggest, from looking at heat transfer only, that the conformal channels should be positioned according to the thermal diffusivity of the tool material. They developed a relationship to this effect. On the other hand, Delgarno and Stewart (2001b) propose that the channels should at least be a diameter from each other and from the mould surface in order to preserve the structural integrity of the mould. These two opinions need to be reconciled. Dalgarno and Stewart (2001b) also investigated the benefits of conformally cooled production injection moulds that were produced by SLS. Their investigation focused on cooling time and tool production life span. They did not complete their investigation on tool durability but based their analysis on the experience of their industry partners. Although not all designers of injection tooling will have the experience of Dalgarno and Stewart's industry partners, their work would form a basis of further work on SLS injection moulds.

Dimla et al (2005) give an indication of the state of art of cooling with conformal channels. Dimla et al reiterate the view of previous researchers that conformal channels provide better cooling than conventional cooling. They however point out more work is required on the interplay of heat transfer, durability, pressure and stress reduction in the design and deployment of cooling for injection moulds. Most of the investigations have been done on simple geometries. It is also not known if the alleged benefits can be extended to complex geometries. It should also be recognised that flow rate of the coolant is a critical parameter for the cooling process. Despite the geometry, if the flow rate and heat capacity of the coolant are small; the coolant will warm up as it flows through the mould, thereby producing uneven temperature. None of the researchers have investigated the use of other coolants apart from water.

3 THERMAL PERFORMANCE OF THE TWO COOLING TECHNIQUES

The thermal performance of a typical injection mould shown in Figure 1 was modelled using the *K*-ε model with enhanced wall treatment for solution of the Navier-Stokes equations and the energy equation for the coolant. The mould was modelled using the energy equation and the continuity equation for the solid. The equations are discretised and a two dimensional mesh was generated using Gambit^{TM}. The resulting model was then solved using Fluent^{TM} using water as a coolant with a velocity of 4 m/s and an inlet temperature of 15 ° C. Instead of alumina, aluminium was used as the mould material with a constant flux of 40000 W/m^2 for the mould surface.

Figure 1 presents a typical two dimensional temperature distribution of a mould with conventional cooling. The figure indicates that a constant mould temperature was not achieved for the above conditions, higher temperatures developed in areas furthest from the holes. Figure 2 which shows that although we might expect a conformally cooled mould to achieve an even temperature distribution, the distribution is still uneven despite the modification. Higher temperatures are now experienced in the middle sections of the mould. This suggests that more work is required to determine the channel configuration that would give uniform temperature distribution.

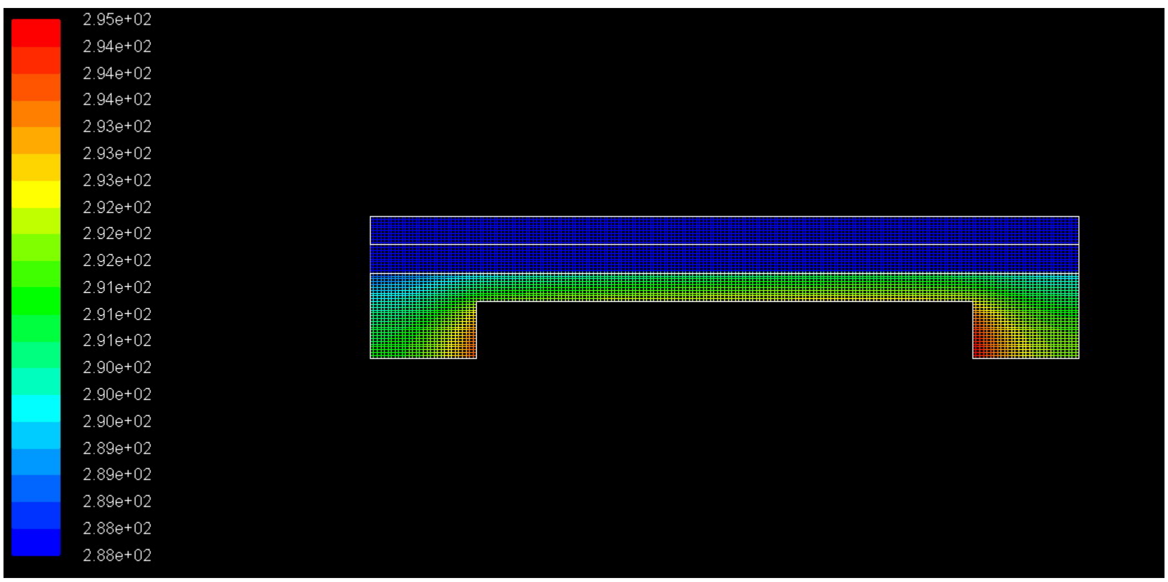

Figure 1: Temperature distribution for a mould with conventional cooling

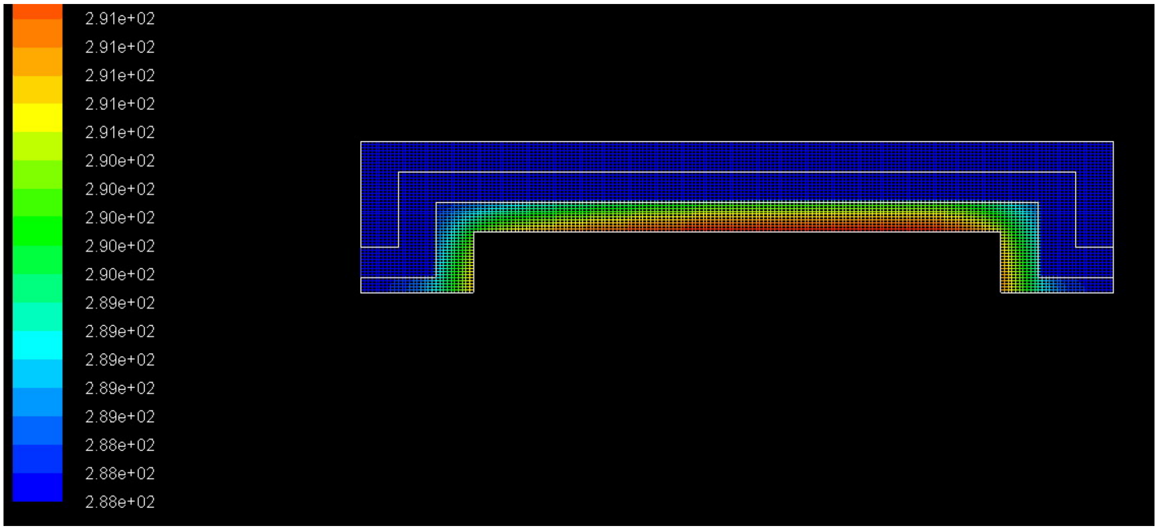

Figure 2: Temperature distribution of conformally cooled moulds

Although none of the previous researchers studied pressure drop for various configurations of the cooling channel, it is realised that pressure influences the pumping power required hence the operating cost of the cooling equipment. Figure 2 and 4 show pressure drop across conventionally and conformally cooled moulds respectively. The figures show that, for the design that was tested, pressure drop across conformally moulds was at least 32 times more than that of conventionally cooled moulds. This presents a tremendous increase in pumping power. Thus further development of conformal cooling should seek also to minimize the pressure drop.

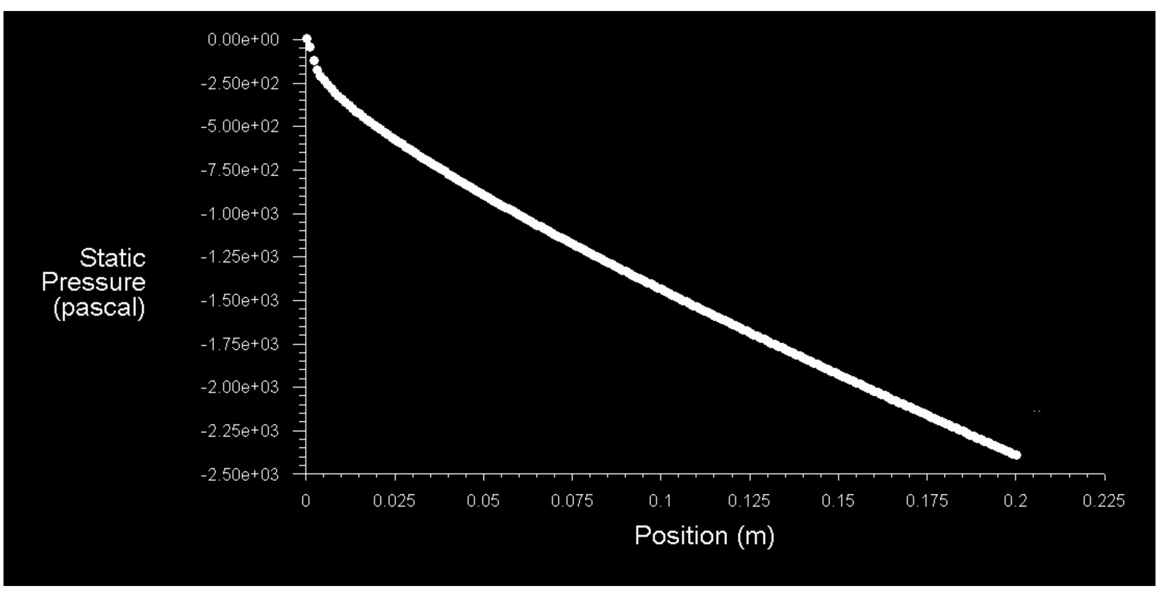

Figure 3: Pressure Drop along a Conventional Cooling Channel

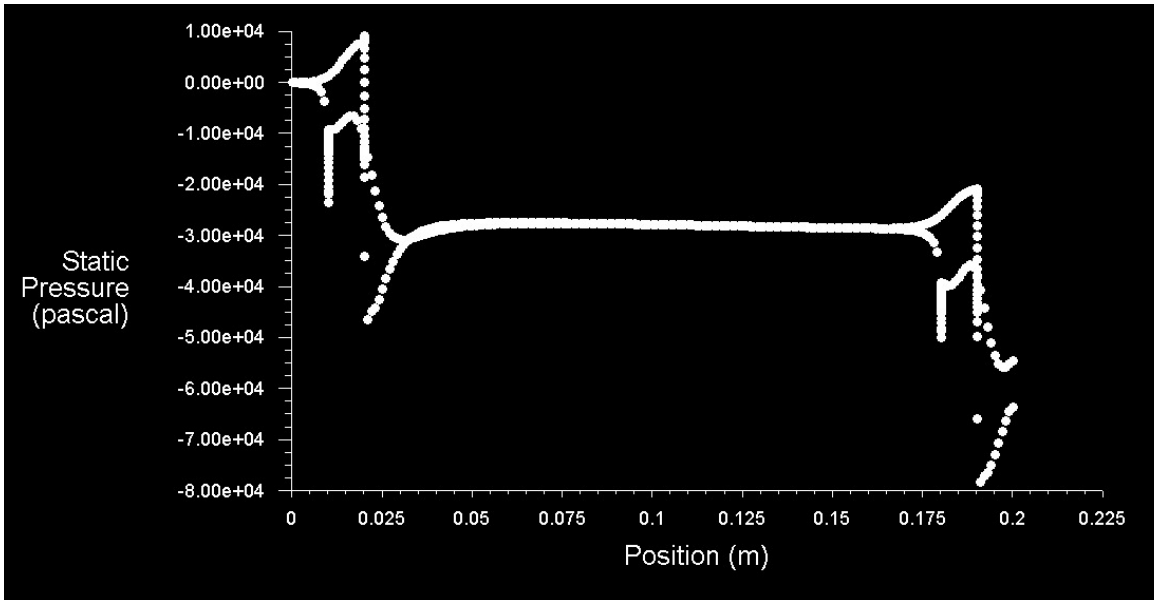

Figure 4: Pressure Drop along a Conformal Cooling Channel

The above results from the simulations give an indication of the deficiencies of current thinking on cooling of injection moulds. However, more work is required in order to validate the ideas presented in this paper before any definitive conclusions can be drawn. The analysis should be extended to 3 dimensions in order to accurately portray the temperature and stress distribution in the mould. It is evident that if 3 dimensional analysis if the mould is attempted, more uneven distribution would be observed

4 CONCLUSION

Conformal cooling offers more benefits than conventional cooling. However, it is evident that in its present form conformal cooling does not adequately address the cooling problem. More work is required to fully exploit the benefits offered by conformal cooling it terms of high mould cooling rates and even mould surface temperatures while maintaining mould structural integrity. It has been suggested that 3 dimensional modelling should be undertaken to more accurately portray the temperature and stress distributions for the present mould set-up.

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